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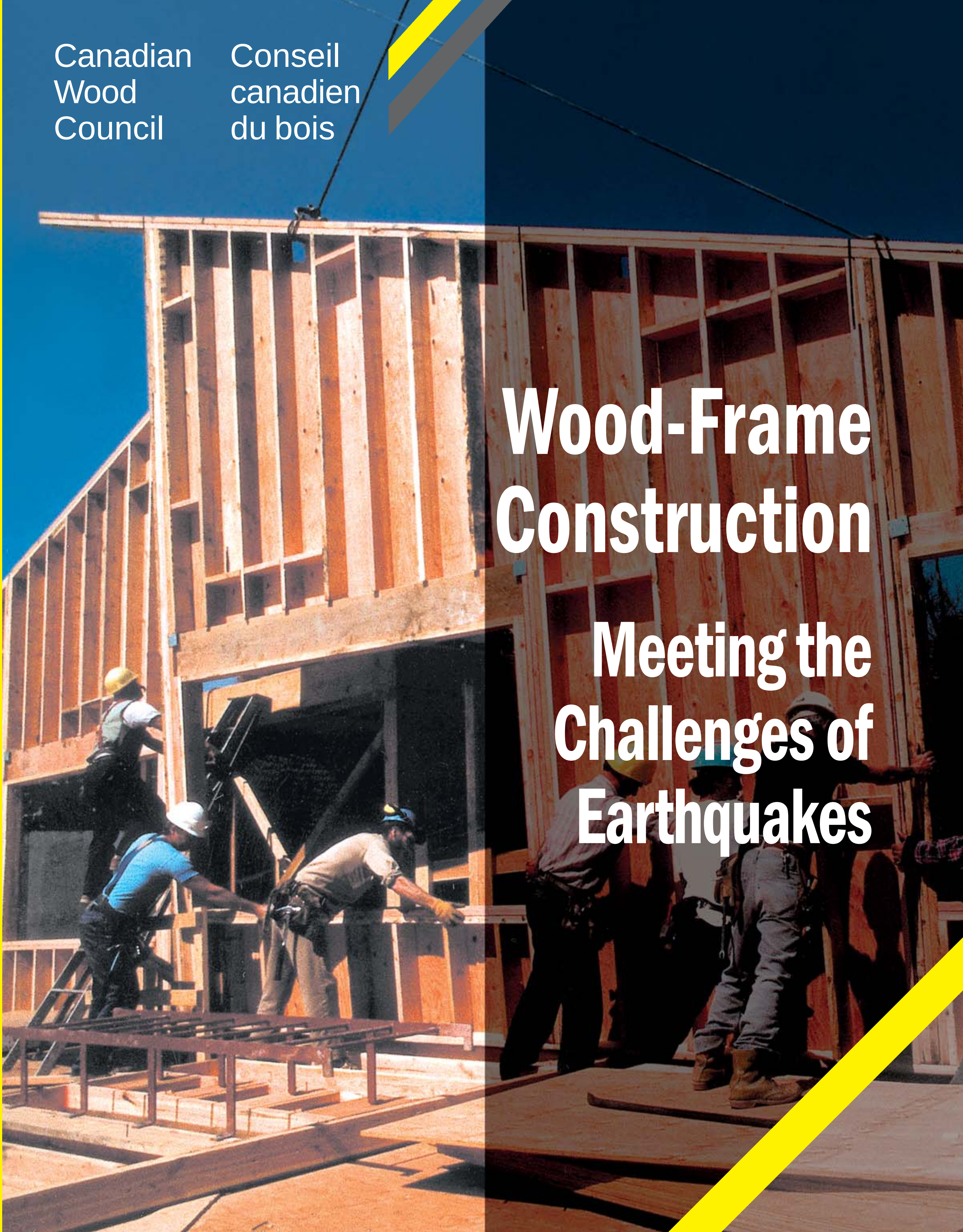

Wood-Frame Construction

Meeting the Challenges of Earthquakes

Building Performance Series No. 5

Building Performance Bulletin

Photo: Bay Area Regional Earthquake Preparedness Project

The Canadian Wood Council is the national association representing Canadian manufacturers of wood products used in construction.

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Introduction

North American single-family homes are considered by many to be the safest place to be in an earthquake. This is not surprising considering that North American housing is almost synonymous with wood-frame construction. The lightweight and high energy absorbing capabilities of wood framing provides a system strong enough to withstand the effects of powerful earthquakes. Experience from strong earthquakes, in North America and around the world, has shown that well-constructed wood-frame buildings provide safety to their occupants.

There are over a million earthquakes annually but most are too small to be felt. Although earthquakes can occur anywhere, there are certain locations where the likelihood of strong earthquakes is particularly high. Around the world, earthquakes claim many lives each year — many from damage to buildings. There have been relatively few deaths in recent North American earthquakes. This can be attributed to North American building practices, including the widespread use of wood framing for housing.

The 1964 earthquake in Prince William Sound, Alaska was one of the most powerful earthquakes ever recorded in North America. Considering the magnitude of the earthquake relatively few lives were lost. Measuring 8.4 on the Richter scale, the earthquake claimed only 131 lives and 122 of these resulted from the tidal waves caused by the earthquake. By contrast, 15,000 people were killed in the

1999 earthquake in Turkey that measured 7.4 on the Richter scale.

The Geophysical Institute of the University of Alaska explains the relatively low losses in the 1964 Alaska Earthquake as follows:

> *"The number of deaths from the earthquake totalled 131; 115 in Alaska and 16 in Oregon and California. The death toll was extremely small for a quake of this magnitude due to low population density, the time of day, the fact that it was a holiday, and the type of material used to construct many buildings (wood)."*[1]

In California, there are over 400 million square feet of public schools and 80% of this area is wood-frame construction. An assessment of the damage to school buildings in the 1994 Northridge Earthquake was summarized as follows:

> *"Considering the sheer number of schools affected by the earthquake, it is reasonable to conclude that, for the most part, these facilities did very well. Most of the very widespread damage that caused school closure was either nonstructural, or structural but repairable and not life-threatening. This type of good performance is generally expected because much of the school construction is of low-rise wood-frame design, which is very resistant to damage regardless of the date of construction."*[2]

In 2002, the State of California Department of Government Services (DGS) completed a legislated inventory and earthquake worthiness assessment[3] of schools. School buildings that were constructed of steel, concrete, reinforced masonry or mixed systems, designed between 1933 and July 1, 1979 were required to be evaluated. Older wood-frame schools were exempted from the assessment on the basis that, *"Wood-frame buildings are known to perform well in earthquakes."*[3]

These endorsements of the ability of wood-frame construction to perform well in the face of earthquakes are based on several researched and documented wood building system characteristics.

1. The attachment of sheathing and finishes to the numerous wood joists and studs in a typical wood-frame house provides redundant load paths for the earthquake forces. There are numerous small connections rather than few large-capacity connections. If one connection is overloaded, its share can be picked up by adjacent connections.
2. Wood has a high strength to weight ratio and therefore wood buildings tend to be lighter than other building types. Lightness is an advantage in an earthquake.
3. The nailed wood connections in wood-frame systems allow the building to flex thereby absorbing and dissipating energy during an earthquake.
4. In engineered wood-frame buildings, structural panels (plywood or OSB) acting in combination with studs and joists, create shearwalls and diaphragms — very effective lateral-force resisting building assemblies.

This Building Performance bulletin is intended to improve the understanding of earthquakes and their effects on wood-frame buildings. Except for a few exceptional cases, hundreds of thousands of wood-frame buildings have provided protection for their occupants when exposed to the devastating effects of severe earthquakes. The traditional North American wood-frame house provides the fundamental elements for seismic resistance and wood-frame building practices are continually evolving. New wood-based materials have been introduced, building research has provided better details and lessons learned in past earthquakes are being used to build better houses.

"Wood-frame buildings are known to perform well in earthquakes."[3]

Effect of Earthquakes on Wood Buildings

What Happens in an Earthquake

Most earthquakes originate from the regions at the junctions of the plates that make up the earth's crust. These plates are constantly shifting, creating stresses and distortions. Where the stress is greater than the strength of the crust, there will be a sudden slippage that releases energy and causes seismic waves on the earth's surface. The place where the energy is released is called the focus of the earthquake, and the point on the earth's surface directly above the focus is called the epicentre. (Figure 1)

The amount of energy released at the epicentre is typically measured using the Richter Magnitude Scale (M). A magnitude M4 earthquake can be distinctly felt near the epicentre, M5 and M6 are moderate size earthquakes that may cause considerable damage, and M7 and M8 are often accompanied by wide-spread damage to buildings and other structures and can trigger landslides and permanent ground displacements.

If a building is located directly over a fault, it can be damaged by failure of the ground below the foundation. Unstable slopes and weak soil deposits can lead to foundation failure and damage or collapse of the building. However, most damage is a result of ground motions from the seismic waves radiating from the earthquake epicentre.

When the ground motion is strong enough, it moves buildings. The earthquake moves the foundation but inertial forces try to keep the upper storeys of the building in their original positions. (Figure 2) If ground displacement were to occur very gradually, the building would ride along easily, however, earth-quakes involve rapidly accelerating ground forces. The forces generated in the earthquake depend on the weight of a building and how quickly the ground accelerates. Since inertial forces are greater when objects are heavier, earthquake forces are higher in heavier building. Likewise, higher ground accelera-tions create more stress in the structure. Earthquakes will affect buildings differently depending on the characteristics of the ground motion and character-istics of the building structure.


Photo: Bay Area Regional Earthquake Preparedness Project

Exterior view of a wood-frame house illustrating damage caused by ground failure. Note cracks in the pavement at the front of the house.

Figure 1: Earthquake Basics

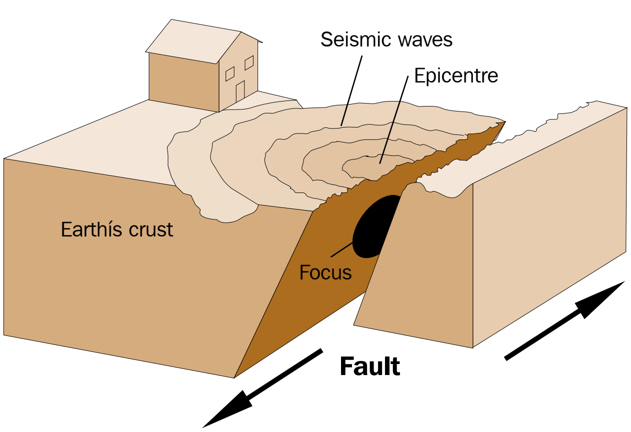
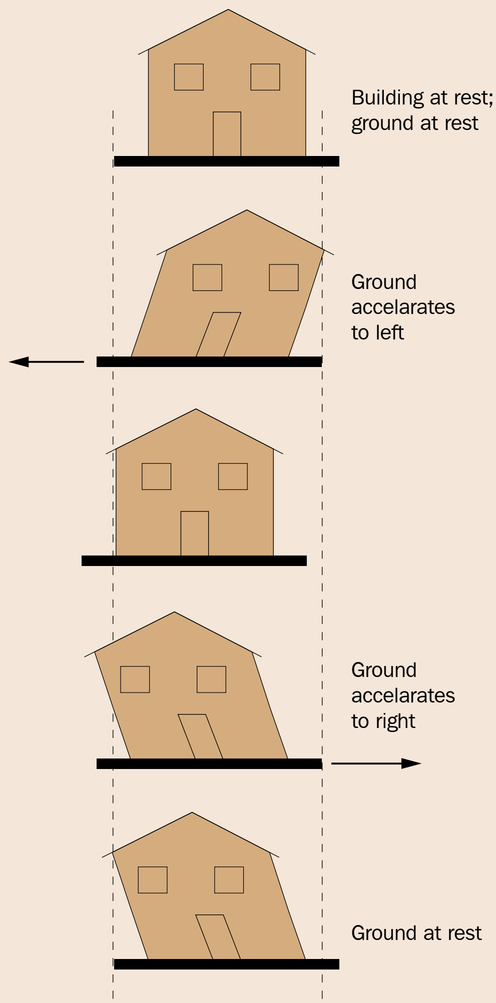


Figure 2: When the Ground Moves



The type of seismic ground motion at a building site is dependant on a number of factors:

- Distance of the building from the earthquake's epicentre,
- Magnitude of the earthquake,
- Depth of the earthquake's focus, and
- Soil conditions at the building site.

The way that a building responds to an earthquake depends on the size of the building and its stiffness characteristics. Earthquakes that have high peak ground accelerations pose the greatest challenge to wood-frame buildings. Measured ground accelerations, g, are recorded as a fraction of the acceleration due to gravity (10 m/s^2 or 32 ft/s^2) and are greatest at the epicentre. Although the Richter scale is often used to characterize an earthquake, peak ground acceleration at a given location is a better indicator of the potential damage of earthquakes on wood-frame buildings.

The Response of Wood-Frame Construction to Earthquakes

In North America, most building codes recognize two types of building design and construction: 1) engineered design and construction and 2) design and construction by conventional rules.

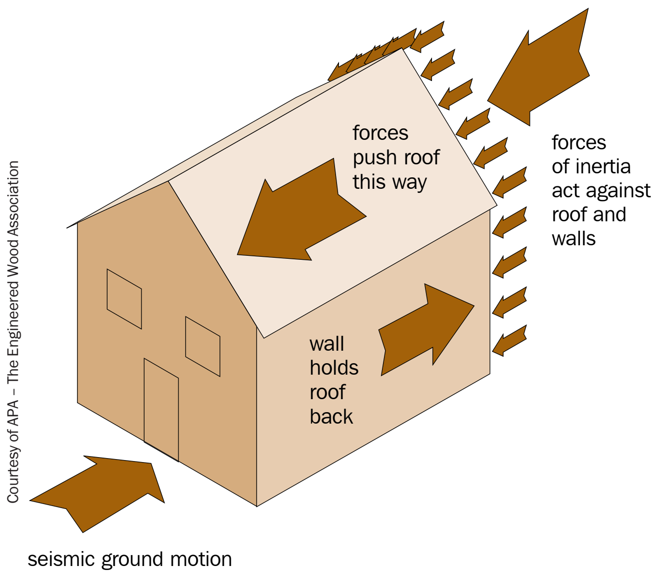
Engineered construction uses fully designed systems, by engineers, to resist the calculated imposed loads. Conventional construction is based on a set of prescriptive rules derived from traditional construction practice that have evolved to reflect research findings, and past performance. Conventional construction is limited by building codes to smaller buildings with limited occupancies. Large houses and most non-residential buildings are engineered.

The inertial forces generated by the ground movement of the earthquake, concentrate lateral forces in the roof and floors where the mass of the building is greatest. The forces in the roof and floors must be resisted by walls and the entire structure must be adequately connected to the foundation. (Figure 3) The following components of wood-frame construction are critical to the resistance of seismic forces:

- Anchorage to the foundation,
- Strength and ductility of the walls,
- Strength and continuity of the horizontal floors, roof and ceilings, and
- Interconnection of all of the framing elements.

Conventional construction guidelines typically prescribe minimum roof, wall and floor constructions and the connections between them. Braced walls that meet minimum requirements with respect to sheathing length and type of sheathed wall must be spaced at regular intervals in the building. Anchor bolt requirements are specified to ensure that the structure is adequately tied to the foundation.

Figure 3: Seismic Forces on a Building



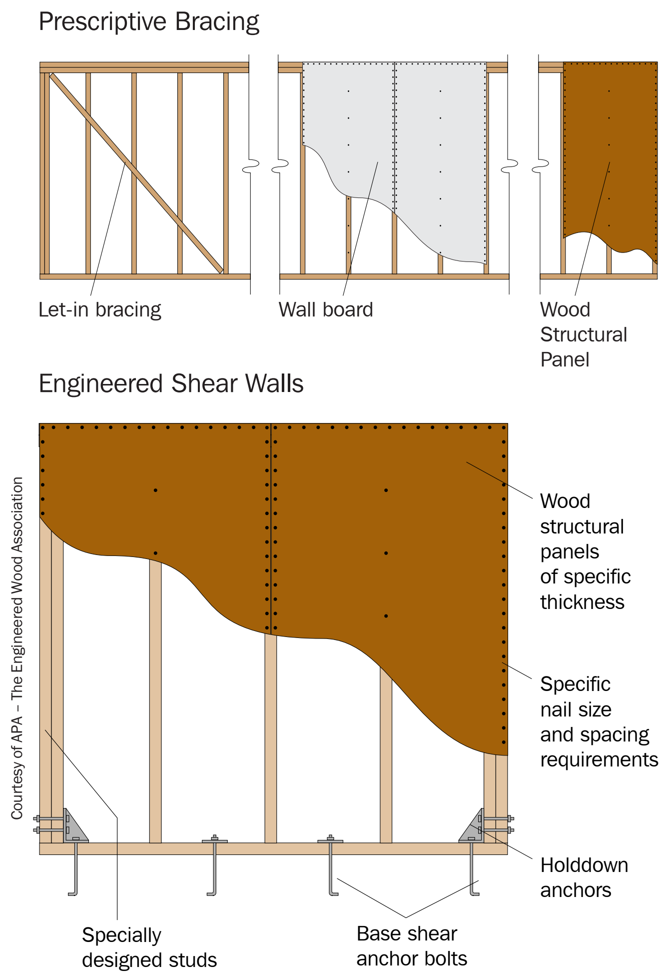
Typical construction often exceeds the minimum conventional requirements in the building codes. For example, wall sheathing is often thicker than the specified minimum thickness and typically there are more walls in a building than the minimum braced wall requirements.

In engineered design, a lateral load path is established and each element of the load path is designed and detailed to resist the calculated earthquake force. Roofs and floors are designed as diaphragms and some of the walls in the building will be designed as shearwalls. The design of shearwalls and diaphragms includes ensuring that:

- Structural wood sheathing (OSB or plywood) is thick enough to resist the calculated forces,
- Nailing is adequate to transfer the shear forces in the sheathing to the roof, floor or wall framing,
- Blocking is specified at the edges of the structural sheathing in the diaphragms and shearwalls, if necessary, and
- Framing members around the perimeter of the diaphragms and shearwalls are strong enough and properly spliced to resist the calculated tension and compression forces.

Engineered design also requires adequate connections between all of the elements in the load path. Therefore, additional nails or special framing anchors are typically required to connect the diaphragms to the shearwalls. Special “hold-down” connections are used to hold down the corners of the shearwalls and additional anchor bolts are usually required to connect the shearwall to the foundation. (Figure 4)

Figure 4: Shear Resisting Elements



Wood-frame buildings have properties that naturally enhance their performance in earthquakes, although to ensure that wood-frame buildings are safe in earthquakes, good construction practices must be followed. Some of these properties are described in the following:

Strength and Stiffness:

The lateral forces of an earthquake tend to distort the building so the walls rack (become unsquare). Braced walls or shearwalls are critical for providing racking resistance during an earthquake. Walls constructed with plywood or OSB structural sheathing are very effective in resisting the racking forces of earthquakes. In locations where strong earthquakes are possible, the stiffness and resistance of the walls can be augmented by increasing the thickness of the structural panels and increasing the number or size of the nails. In addition, research and experience have shown that 'non-structural' elements contribute to the lateral resistance of the structure. For example, interior finishes, partitions, and many types of exterior cladding contribute to the lateral resistance of the structure.

Ductility:

Compared to other materials such as masonry and concrete that have to be carefully designed and detailed to ensure good seismic performance, wood systems are inherently more ductile. Ductility is the ability of the structure to yield and to deform without collapse. It is desirable for a building to have some flexing capability when subjected to the sudden loads of an earthquake because the flexing allows the building to dissipate energy. The numerous nailed joints are very effective in providing ductility to wood-frame buildings.

Weight:

Wood-frame construction is lightweight. Concrete walls used in ICF (insulated concrete form) wall construction are about 7 times heavier than typical wood-frame walls. Since forces in an earthquake are proportional to the weight of the structure, lightweight wood-frame buildings that are properly designed and built can be expected to perform very well in earthquakes.

Redundancy:

Buildings that have numerous load paths are considered structurally redundant and provide an extra level of safety in earthquakes. Structures supported by heavy frames rely on relatively few structural members and connections. A design or workmanship flaw in any one component may mean overloading of adjacent load paths. Typical wood-frame construction is comprised of hundreds of structural elements and thousands of nail connections. This means that the failure of one load path can often be compensated for by adjacent members and joints.

Connectivity:

Wood-sheathed walls can resist the racking forces of an earthquake, but a building must also be designed and built to resist sliding or overturning. In either case, the building must be adequately secured to the foundation. The connection of the walls, floors and roof framing make the house a single solid structural unit and is an important feature for holding a house together during an earthquake.

Performance of Wood-Frame Buildings in Past Earthquakes

In North America, the design of houses and other buildings for earthquakes has been primarily to minimize serious injury or death to people, and wood-frame construction has generally met this requirement very well. In Canada, the objective of earthquake-resistant design is to prevent major failure and loss of life. According to the Structural Commentaries to the National Building Code of Canada:

> *"Structures designed in conformance with these provisions (of the 1995 National Building Code of Canada) should be able to resist moderate earthquakes without significant damage and major earthquakes without collapse."*[4]

A survey of the performance of wood-frame construction in earthquakes shows a remarkably low fatality level (Table 1). Most of the residential buildings in the survey areas were built according to conventional practice and were not specifically designed by engineers.

The vast majority of wood-frame buildings survived the strong shaking almost unscathed or with various degrees of superficial and structural damage. A few wood-frame buildings with recognized structural deficiencies collapsed. A summary of the deficiencies is given in the next section.

Three recent California earthquakes provide insight into the performance of North American style wood-frame construction.

San Fernando Earthquake, 1971

The earthquake occurred in a northerly suburban area of Los Angeles and consequently affected a large number of single-family homes as well as hospitals and commercial structures. Hospitals and office buildings built of unreinforced masonry and reinforced concrete collapsed, or were severely damaged to the point where they had to be demolished.

Photo: E.V. Leyendecker, U.S. Geological Survey

Table 1: Performance of wood-frame construction in earthquakes[5]

Earthquake	Force		Approximate No. of Persons Killed		No. of Platform Frame Wood Buildings Strongly Shaken (estimated)
	Richter Magnitude M	Maximum Peak Ground Acceleration Measured g***	Total	In Failures of Platform Frame Wood Buildings	
San Fernando, CA, 1971	6.7	0.6+	63	4	100,000
Edgecumbe NZ, 1987	6.3	0.32	0	0	7,000
Saguenay QC, 1988	5.7	0.15	0	0	10,000
Loma Prieta CA, 1989	7.1	0.5	66	0	50,000
Northridge CA, 1994	6.7	1.0	60	16 + 4*	200,000
Hyogo-ken Nambu, Kobe Japan, 1995	6.8	0.8	6300	0**	8,000**

* 16 deaths occurred in the collapse of one apartment building. Four deaths were from foundation failures that caused collapse of buildings on hillsides.
** Pertains to modern North American style wood-frame houses in the affected area.
*** Numbers taken from Rainer and Karacabeyli document.[6]

Photo: E.V. Leyendecker, U.S. Geological Survey

Aerial view of the damage to the San Fernando Veterans Administration Hospital and complex. The collapsed masonry structure was built in 1926, before earthquake building codes were in effect. Forty-seven deaths occurred as a result of the collapse of the structure.

The majority of the wood-frame houses performed well, especially from the standpoint of life safety. Damage in older wood-frame houses in the San Fernando area ranged from superficial to partial collapse. Serious damage included houses sliding from foundations, collapse of "cripple walls" in crawl spaces, collapse of add-ons such as porches and collapse of masonry chimneys. Newer two-storey apartment buildings with large ground-level openings were also severely affected. Typically, these apartments were constructed to allow parking at the ground level. Because one wall of the garage storey was open, these floors were "soft storeys."[6]

The importance of providing strong walls and foundation connections was recognized in this earthquake and building codes were updated accordingly.

Photo: C. Stover, U.S. Geological Survey

Loma Prieta Earthquake, 1989

The epicentre of the earthquake was located 100 km south of San Francisco but its effects were felt on the North Shore of San Francisco Bay. The earthquake caused the collapse of a number of engineered structures including the double-deck freeway in Oakland that resulted in the death of 49 motorists. At the epicentre, housing was subjected to peak ground accelerations as large as 0.5 g and possibly larger. Newer housing at the epicentre generally performed well unless they were situated on ground fissures or had large openings in lower storey walls.[6]

Some older housing at the epicentre experienced extensive damage due to inadequate braced walls, cripple wall failures and inadequate connections to the foundations. In the Marina District of San Francisco some older four-storey buildings were particularly susceptible due to ground storey parking that resulted in non-reinforced soft storeys.[7]

Northridge, 1994

The earthquake struck the densely populated San Fernando Valley, in northern Los Angeles on January 17th, 1994. Although moderate in size (M6.7) the peak ground accelerations were amongst the highest ever recorded and significantly higher than those specified in the building codes at the time.[8] There were numerous building collapses, many in large structures. Amongst the reasons given for the limited death and injuries from the earthquake was the time of the earthquake:

"The earthquake occurred at 4:31 a.m. when the majority of people were sleeping in their wood frame single family dwellings, generally considered to be the safest type of building in an earthquake. If the earthquake had occurred during the day, say at 11:00 a.m., several hundred people would have been killed at the retail store and parking garage of the Northridge Fashion Mall alone, where actually only one person was killed. Also, due to timing of the earthquake, people were not present on sidewalks to be injured from falling debris, particularly from unreinforced masonry and tilt-up buildings or falling facades from other buildings." [9]

The 1994 Northridge Earthquake has been extensively studied. A very high percentage of wood-frame houses performed well in the earthquake. Most of the damage to such buildings was non-structural in nature and easily repairable.[2]

There were several typical modes of failure that had been experienced in previous earthquakes. Although building codes had addressed these issues in new construction, the failures reflected the need to upgrade existing buildings to remove obvious deficiencies. In the Northridge Earthquake, a vulnerable wood-frame building type was low-rise, multi-storey, apartment structures with a soft first storey. Such buildings, with large, often continuous openings for parking, did not have enough wall area and strength to withstand the earthquake forces and resulted in several collapses of the ground floor. The most tragic collapse of the earthquake occurred when 16 people died in one such apartment building. Although the building was engineer-designed, the peak ground acceleration at

Photo: J. Dewey, U.S. Geological Survey

The second level of the concrete parking structure of the Northridge Fashion Center collapsed onto the lower level.

Photo: J. Dewey, U.S. Geological Survey

Overall wood-frame housing performed well in the Northridge earthquake. In front of this San Fernando Valley house, the sidewalk tented due to strong ground shaking although the house did not sustain visible damage.

that location was substantially greater than the 0.4 g design value used in the building codes at the time.[6]

Other wood-frame construction performed exceedingly well. In a statistical-based study of the seismic performance of residential construction in the Northridge earthquake, the authors concluded:

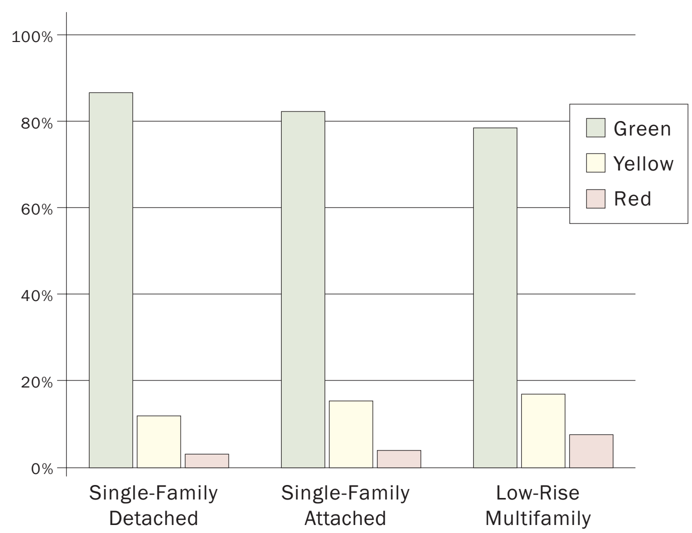
> **"SFD (Single family dwelling) homes suffered minimal structural damage to elements that are critical to the safety of occupants. Structural damage was most common in the foundation system. The small percentage of surveyed homes (approximately two percent) that experienced significant foundation damage were located in areas that endured localized ground effects or problems associated with hillside sites."[10]**

Following an earthquake, it is necessary to ensure displaced people can be provided with emergency accommodation. If too many houses are destroyed, emergency shelters will be overwhelmed. In the days after the Northridge Earthquake, many buildings in the Los Angeles area were inspected to determine if they were safe for occupancy. When there was concern about the safety of a building, an initial inspection was carried out and the building was tagged either "Red" for hazardous, "Yellow" for buildings that posed a threat to life, but not so much that an occupant could not re-enter to remove possessions and "Green" for buildings that did not pose a life-safety hazard to the occupants. After 4 days, almost 50,000 residential buildings had been inspected and over 85% of these were "Green Tagged" (Figure 5).

Most of the buildings were inspected because residents and owners were concerned the condition of their homes might be unsafe. Therefore the buildings inspected were generally more damaged than the vast majority of wood-frame buildngs for which no inspection was requested. Furthermore, many of the red and yellow-tagged buildings were subsequently revised to green.[10]

Survey results have shown that in a number of earthquakes wood-frame construction has withstood peak ground accelerations of 0.6 g or greater without serious distress and often without any signs of structural damage. Most of the wood-frame houses that experienced the strong earthquake forces in California were built using the prescriptive conventional construction requirements.

Figure 5: L.A. Department of Building and Safety Building Inspection Results



Lessons Learned from Past Earthquakes – Improving Performance for the Future

The evaluation of building performance has identified problems with some wood-frame buildings even though, overall, wood-frame buildings have been found to be safe in earthquakes. These deficiencies are described in brief to provide an understanding of failure modes and how they can be avoided.

Photo: D. Perkins, U.S. Geological Survey

Shored building in the Marina District of San Francisco following the 1989 earthquake. Note the garage area on the first floor beneath the apartments that created a weak first storey.

Weak First Storey: Experience in past earthquakes has shown that weak and soft first storeys will make buildings susceptible to the effects of earthquakes. Providing adequately braced or sheathed walls is essential to ensure conventionally built wood-frame buildings can resist earthquakes. Large openings in the walls such as windows, doors and garage doors can leave too little wall area to provide adequate resistance to the lateral forces imposed by earthquakes. Unless these walls are adequately reinforced, lack of wall capacity leads to large distortions and eventual collapse. California experience has shown that multi-family apartments built with first storey garages are particularly vulnerable to earthquakes and building codes have recognized that buildings with soft storeys have to be carefully designed and detailed to resist earthquakes. Engineering solutions can be provided for new or existing structures that require additional wall reinforcement.

Connections to Foundations: Anchor bolts are used to prevent a structure from moving off its foundation. Some old houses were built without using anchor bolts to connect the wood structure to the foundation. Experience has shown that these structures may slide off their foundations during an earthquake. These structures can be retrofitted by adding connections between the wood framing and foundation.

Photo: E.V. Leyendecker, U.S. Geological Survey

This turn-of-the-century wooden residence sustained major damage when it moved off its foundation in the 1989 Loma Prieta Earthquake.

Photo: C. Stover, U.S. Geological Survey

Failure of cripple wall in the Loma Prieta Earthquake.

Cripple Walls: Cripple walls, also known as knee walls or pony walls, are the short stud walls between the floors and foundations in some houses. Many older buildings that had unbraced cripple walls sustained structural damage during California earthquakes. Strengthening the walls using wood structural sheathing is an effective method of bracing cripple walls.

Chimneys: Unreinforced masonry chimneys are particularly susceptible to earthquake damage. Failure of the chimneys can cause damage to the roof and walls of the structure below. Also, damaged chimneys may be dangerous in aftershocks following the initial earthquake. Bracing chimneys or using chimneys from lighter materials can help prevent damage in future earthquakes.

Unrestrained Furnishings, Components and Appliances: Tall objects such as bookcases can topple, and sliding or rolling objects can become projectiles. Heavy, unbraced interior partition walls can fall over, and improperly attached canopies and curtain walls (for example, brick cladding) can fall on passers-by. Domestic gas water heaters, unless properly braced and secured, can easily tip over or displace, causing a possible leakage of gas and the risk of explosion. Bracing furnishings, components and appliances can be a cost effective way of reducing earthquake damage and costs.

Building codes are continuously evolving to address structural issues related to earthquake safety but they do not typically deal with furnishing and appliances nor do they address existing buildings. Increasingly homeowners in areas prone to earthquakes are assessing their houses or having their houses assessed by professionals. Homeowners can easily undertake many of the upgrades themselves. Government agencies provide upgrade information and much of it is available electronically. The Association of Bay Area Governments at **www.abag.ca.gov** and the California Seismic Safety Commission at **www.seismic.ca.gov** both have useful information for homeowners and building professionals. In Canada, the Canada Mortgage and Housing Corporation has prepared a Residential Guide to Earthquake resistance.[11]

Photo: J. Dewey, U.S. Geological Survey

Chimney damage from the Northridge Earthquake.

Photo: U.S. Geological Survey

These overturned bookcases are typical of the damage that can occur during a strong earthquake.

Research

Wood-frame construction has benefited from many research projects ranging from tests on the smallest nail to full-scale earthquake simulations on whole houses. The observed seismic performance of traditional wood-frame construction is difficult to model mathematically due to the many load paths and contributions of "non-structural" elements. By gaining a better understanding of the properties of materials and assemblies, researchers are better able to predict the performance of whole houses. Full-scale assemblies are being used to develop sophisticated models of how a whole house works together to resist earthquake loads. This research helps to explain the performance of conventional wood construction and can be used to provide more effective design solutions.

Forintek Canada Corporation is Canada's foremost wood research institute and has an ongoing multi-phase seismic research program focusing on component testing and modeling. Results from their research were used to augment the seismic provisions in the Canadian wood design standard. Forintek and its research partners have also worked on computer models used to evaluate the performance of wood-frame buildings in earthquakes and this work shows promise as a tool that can help to efficiently design earthquake-resistant wood-frame buildings.[12]

Tests on full-scale wood-frame buildings were undertaken as early as 1965.[12] Since then, there have been other tests at research institutions around the world. The more recent tests involve using a "shake table" to closely simulate the effects of a real earthquake. Of particular interest is the CUREE project in California. A parallel research project was carried out at the University of British Columbia (UBC).

Photo: A. Filiatrault, UC-San Diego, CUREE-Caltech Woodframe Project

Full-scale shake tests involved the construction of a house on a special platform capable of simulating earthquake loads of different magnitudes.

The Consortium of Universities for Research in Earthquake Engineering (CUREE) (**www.curee.org**.) is a non-profit organization, established in 1988, to advance earthquake engineering research, education and implementation. The project is funded by the US Federal Emergency Management Agency (FEMA) through a grant administered by the California Governors Office of Emergency Services. The CUREE-Caltech Woodframe Project has five components; testing and analysis, field investigations, building codes and standards, economic aspects, and education and research.

The project included full-scale shake tests that involved the construction of a house on a special platform capable of simulating earthquake loads of different magnitudes. Three different shake table projects were conducted: tests of a simplified full-scale two-storey single family house (University of California San Diego), tests of a full-scale multi-storey apartment building (University of California

Berkeley) with tuck-under parking garages, and tests of a simplified box-type wood-frame building model (UBC).

The two-storey house tests included specimens simulating a conventionally framed house and engineered houses. Some specimens were built without finishing materials (bare), and others were finished with stucco. All specimens were subject to at least a 0.5g peak ground acceleration and some of the engineered houses were subject to 0.89g ground accelerations. A review of the test results by Canadian researchers[12] led to the following general observations:

- In all projects, none of the specimens built with finishes (i.e. stucco) reached a "near collapse" state.
- None of the two-storey "bare" specimens tested in the CUREE project reached a "near-collapse" state.
- One three-storey "bare, tuck under garage" specimens tested in the CUREE project reached a "near collapse" state.
- Test results are in substantial agreement with previous surveys of the performance of wood-frame construction.
- The amount of deflection increases with the degree of openings in the walls.
- Deflection in the conventionally constructed house was higher than deflections in the comparable engineered house.
- Adding a stucco exterior finish and gypsum wallboard interior finishes significantly reduces the lateral deflection, reducing the damage to the finished structure substantially.

The CUREE tests at the University of California San Diego and Berkeley, and tests performed at UBC and Forintek have produced many pertinent results that can be applied to the seismic design of North American style wood-frame houses.

The amount and quality of research devoted to wood-frame construction around the world means an increasing ability to understand how earthquakes affect wood structures and how to design them to perform even better.

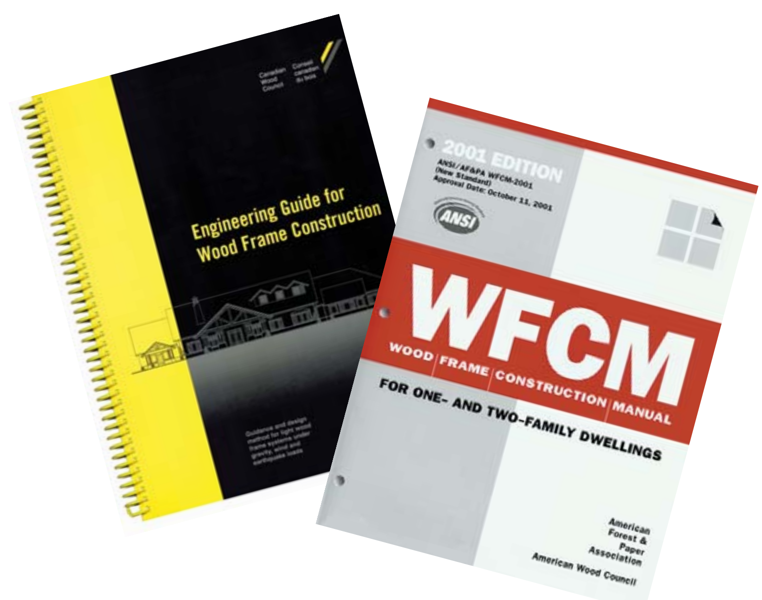
Designing Earthquake-Resistant Wood-Frame Buildings

Construction practices are constantly evolving. For example, longer member spans leading to more open concept structures, larger garages and the desire for more openings in exterior walls have provided challenges for designing earthquake-resistant buildings. However, the widespread use of wood structural panels allows us to build stronger floors and walls and our understanding of earthquake-resistant design is continuously evolving.

North America

In North America, building codes provide prescriptive framing requirements for wood houses. The 1995 and earlier editions of the National Building Code of Canada do not explicitly include prescriptive provisions for earthquake design. Framing guidelines for earthquake-prone regions of Canada can be found in the Canadian Wood Council's (CWC) Engineering Guide for Wood Frame Construction[13] that includes a set of simple prescriptive requirements based on conventional construction guidelines that have been used in California. The CWC guide can also be used to engineer small wood-frame buildings.

In the United States, building codes contain conventional construction requirements for houses that include provisions for earthquakes. Earthquake design

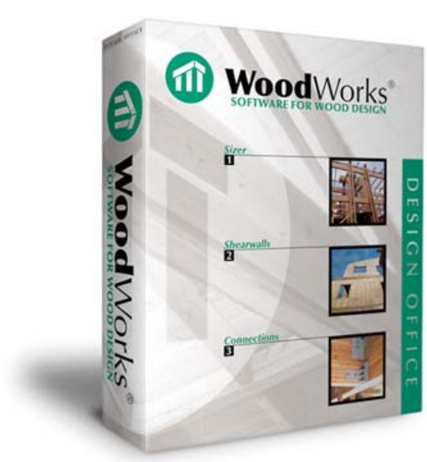


provisions can also be found in the American Forest and Paper Association's Wood-frame Construction Manual for One and Two Family Dwellings[14].

When framing systems are not based on prescriptive requirements, earthquake load paths must be engineered. Loads are determined using the building code requirements and the load-resisting elements are designed and detailed based on the wood design standards. In both Canada and the United States, recent editions of the national wood design standards have been updated to include enhanced provisions for earthquake design. The Canadian Standard Association's latest edition of CSA O86–01[15] "Engineering Design in Wood," includes provisions that make it easier to design wood-frame buildings to resist earthquake loads. Likewise, the most recent edition of the National Design Specification® for Wood Construction[16] in the United States includes all the information required to design wood-frame members to resist earthquake loads.

WoodWorks® Shearwalls design software has been specifically developed to assist engineers to design earthquake-resistant wood-frame buildings. In addition to providing wood design solutions, the software will also generate seismic loads on the building. The software is available for use in both Canada and the United States. Information on the software can be found at **www.woodworks-software.com**.

In North America, building codes and wood design standards provide the information required to design earthquake-resistant wood structures. The codes and standards are updated on an ongoing basis to reflect field studies and research on the effects of earthquakes on wood buildings.



World Demand for Safer Housing

There are many reasons why wood-frame construction, which has been so successfully employed in North America over the past century, is attracting interest in other parts of the world. In some cases, the increasing affluence of emerging economies is creating a demand for increased comfort. In other cases, the failure of buildings and numerous deaths from recent earthquakes is fueling the demand for safer housing.[17]

The entire island of **Taiwan** is exposed to a very high earthquake risk. A 1999 earthquake killed more than 2,200 people and left over 100,000 homeless. As a result, the government has indicated strong support for introducing wood construction and is developing Taiwanese codes based on North American and Japanese Models.

Japan is another country situated almost entirely in a region of high earthquake risk. First introduced 20 years ago, North American style wood-frame construction occupies a fast-growing niche of the Japanese home market, particularly since its exemplary performance during the 1995 Kobe Earthquake.

Increasing economic development is driving the demand for improved housing in **China**. The government has recently adopted modified versions of North American building codes for wood-frame construction that will facilitate construction of high-quality, durable wood-frame housing in China. Like many parts of Asia, areas of China face high exposure to natural hazards like earthquakes and typhoons.

Concrete and masonry are the primary building materials in **Turkey**. The 1999 earthquake in Turkey caused 15,000 deaths, mostly from building collapse, and left 600,000 people homeless. Turkish officials have recognized the need to improve building standards and introduce new construction technologies, including wood-frame construction for single family and low-rise apartment buildings.

In addition to these examples of countries moving toward residential wood-frame construction for earthquake safety reasons, there are many other examples of countries adopting wood-frame construction because it is researched, proven, economical, flexible, and capable of meeting code requirements. Europe and the emerging countries of the former Soviet Union are also showing interest in North American construction technology.

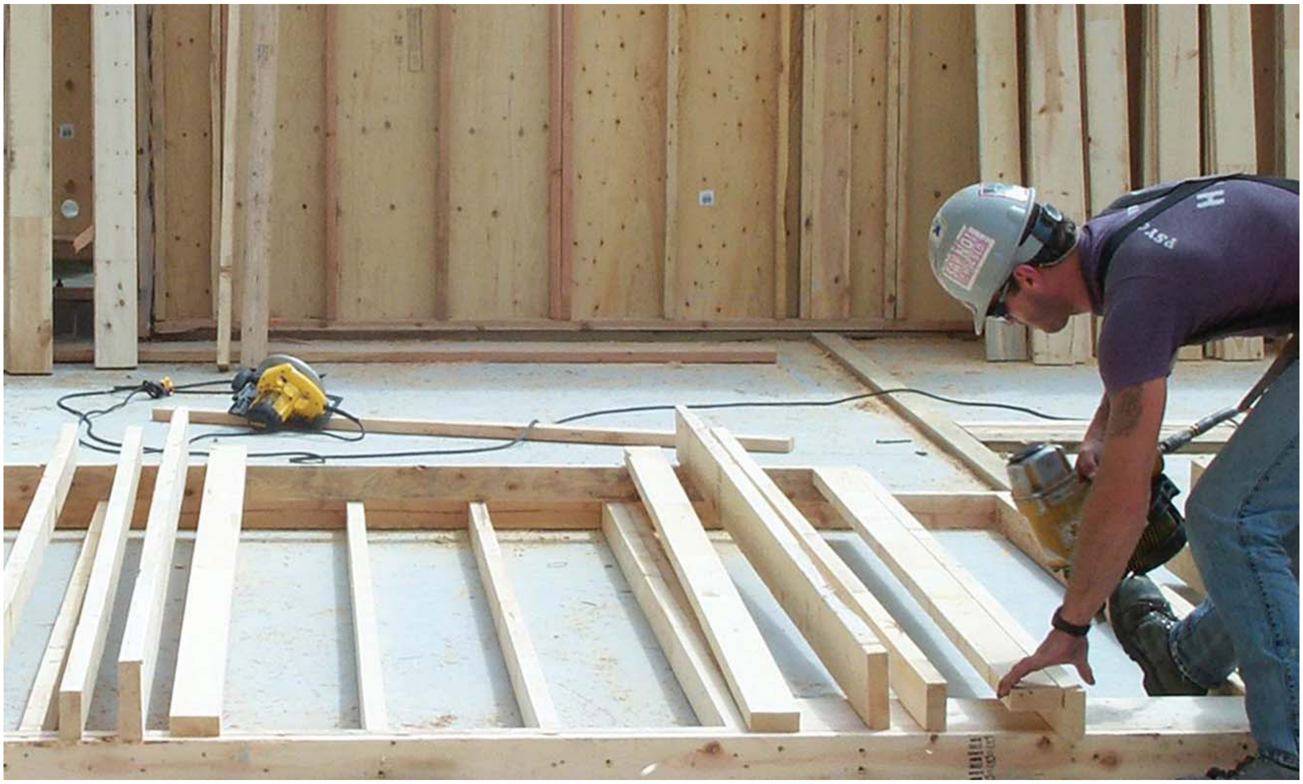


Photo: CANPLY

Conclusions

The lightweight and high energy absorbing capabilities of wood-framing are inherent characteristics that make it a preferred building system in earthquake regions. Surveys have shown that wood-frame buildings meeting the basic requirements for wall bracing, connectivity and anchorage, provide safety to their occupants during earthquakes. The prescriptive requirements of building codes for smaller wood-frame buildings provide a basic resistance to lateral earthquake loads. Larger wood-frame buildings are effectively engineered to resist earthquake forces.

Research has been done on North American wood-frame construction over the past twenty years to better understand and enhance its performance in earthquakes. Wood-frame construction has also benefited from observed performance in North American earthquakes. Test results from research projects are in substantial agreement with the findings of the previous surveys of the performance of wood-frame construction. Building codes and design standards for wood-frame construction are continuously evolving to incorporate earthquake field observations and research.

Wood-frame construction is a proven building method that has provided safety to people in devastating earthquakes. In the Alaska earthquake of 1964, the low death toll is attributed to the fact that most people were at home — in wood-frame buildings — when the earthquakes struck.[1] The same observation was made following the Northridge Earthquake thirty years later.[9] Wood framing also offers the prospect of safety for those people living in areas of the world that are at high risk to the devastating effects of earthquakes.

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